STREAM NITRATE RESPONSE TO DIFFERENT BURNING TREATMENTS IN SOUTHERN APPALACHIAN FORESTS

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ABSTRACT

Southern Appalachian forests are undergoing considerable change due to altered disturbance regimes. For example, fire exclusion has had a major impact on the structure and function of pine–hardwood ecosystems. Recently, fire has been prescribed for a variety of applications: 1) stand-replacement in the form of a mimicked wildfire, 2) site-preparation as part of a fell-and-burn prescription, and 3) understory burning for fuels reduction and wildlife habitat improvement. Assessing watershed-scale responses to burning requires identification of key parameters indicative of changes in structure and function. In the southern Appalachians, nitrogen in the form of NO_3 is a key indicator of ecosystem change or response to disturbance. We compared stream NO_3–N responses among stand-replacement fires (Winespring Creek and Hickory Branch), a fell-and-burn prescription (Jacobs Branch), and a wildfire in an old-growth deciduous forest (Joyce Kilmer). Nitrate–nitrogen concentration increased following two of the four fires. Concentrations following the fell-and-burn prescription fire increased from <0.01 to a maximum of 0.075 mg L^{-1} and remained elevated for 8 months. Similarly, stream NO_3 concentration increased approximately 2 weeks following the old-growth deciduous wildfire from 0.04 to a maximum of 0.50 mg L^{-1} and remained elevated for 6 weeks. There were no significant differences in NO_3 following one of the stand-replacement fires or between treatment and control or pre- and post-burn following the other stand-replacement fire due to maintenance of an unburned riparian area. Although the old-growth deciduous wildfire was essentially an understory burn, the magnitude of stream N response suggests that unavailable recalcitrant forms of N may have been released during the wildfire, as well as a reflection of the potential inefficiency of old-growth forests at sequestering mobilized nutrients. In all cases, hydrologic losses of NO_3–N were insignificant with respect to effects on water quality and site depletion of N.

keywords: disturbance, ecosystems, nitrate response, old growth, North Carolina, prescribed fire, resistance, riparian zone, southern Appalachia, stream.

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INTRODUCTION

Fire is an important agent of change in forest ecosystems throughout the world, but its importance varies among forest types. Effects of fire depend on the quality and quantity of fuels, soil properties, topography, climate, and weather, as well as fire frequency, severity, and intensity. As a disturbance, fire is defined in terms of severity and intensity. Severity is measured in terms of fire residence time and the downward movement of heat (Wells et al. 1979, Van Lear and Waldrop 1989), and has been shown to greatly influence the magnitude of nutrient losses from the system through its effects on forest floor consumption (Richter et al. 1982, Vose and Swank 1993, Clinton et al. 1996). Intensity is defined as the upward heat pulse produced by the fire (Ryan and Noste 1985). For a given forest ecosystem type, variation in both fire severity and intensity is due to the timing and type of fire, and to the availability of fuels.

The onset of fire suppression early in the 20th century significantly reduced the role of fire in shaping the structure and function of ecosystems in the southern Appalachians. In addition, high-grade logging practices (e.g., removal of the highest quality timber) and loss of the American chestnut (*Castanea dentata*) to chestnut blight (*Chryphonectria parasitica*) (Anagnostakis and Hillman 1992) have further altered stand composition and structure. Decades of fire exclusion have resulted in a build-up of woody and fine fuels, which recently has been blamed for some catastrophic fires, as well as the loss of important ecosystems and wildlife habitat historically dependent on periodic wildfire for maintenance (Greenlee 1997, Van Lear and Harlow 2002).

Fire is currently used as a management tool in many forest ecosystems. Properly applied, it can enhance overall stand health and productivity by reducing fuel loadings to avoid catastrophic fire (Sanders and Van Lear 1987, Van Lear and Waldrop 1989). While reducing competition to commercially desirable tree species, fire has been shown to improve habitat for both avian and terrestrial wildlife (Cooper 1971). The application of fire to accomplish these goals is considered an attractive alternative to mechanized techniques of stand improvement, primarily because of reduced costs (Cooper 1971, Abercrombie and Sims 1986). In addition, the reintroduction of fire to southern Appalachian forest ecosystems would re-establish one of the more important naturally occurring distur-

Table 1. Comparison of four watersheds on the Nantahala National Forest, North Carolina. Community types within large burn areas are a mix of xeric and mesic conditions.

Site	Burn treatment	Community type	Burn description	Burn timing	Burn area (ha)
Jacobs Branch	Fell and burn	Mid-elevation oak–pine	High intensity–low severity	September	6
Winespring Creek	Stand replacement	High-elevation oak–pine	Moderate intensity–low severity	Late April	82
Joyce Kilmer	Wildfire	High cove	Low intensity and severity	November	2400
Hickory Branch	Stand replacement	Mid-elevation oak–pine	Moderate intensity–low severity	March	365

bances that shaped vegetation patterns and forest structure in the region. However, its continued use in the southern Appalachians and elsewhere has raised considerable interest in the effects of prescribed fire on ecosystem integrity, particularly how it influences losses of key plant nutrients such as nitrogen. Although usually in greater supply than is needed for plant growth, nitrogen (N) is commonly a limiting nutrient to forest productivity (Keeney 1980, Vitousek et al. 1982) because most is in unavailable organic forms (Vose 2000). Total ecosystem nitrogen may decrease in forested systems following fire (Neary et al. 1984, Rapp 1990) due to volatilization of nitrogen stored in coarse and fine fuels, and/or increased leaching of released NO_3 from the system (Knoepp and Swank 1993). In contrast, increases in total N following burning can result from a combination of increased abundance of symbiotic and non-symbiotic N-fixers. Similarly, N availability often increases due to increased soil moisture and temperature, and decreased plant uptake, making more N available for mineralization (DeBano 1991).

In the southern Appalachians, stream NO_3 concentration has been shown to be a sensitive indicator of ecosystem response to disturbance (Swank et al. 1981, Swank and Vose 1997). Stream N increases due to fire vary greatly among forest types. Neary and Courier (1982) found that wildfires covering more than 30% of the watershed resulted in a three-fold increase in stream NO_3 compared with a control watershed. Douglass and Van Lear (1983) found no increases in NO_3 following low-intensity seedbed preparation burning in the South Carolina Piedmont. In Oregon, Tiedemann et al. (1988) found that harvest without burning resulted in no increase in stream NO_3 concentration. However, in clearcuts with as little as 17% of the area machine piled and burned, they detected significant increases in stream NO_3 concentrations.

An important functional attribute of forest ecosystem health and sustainability is the system's response to disturbance. The resistance–resilience model of ecosystem response to disturbance provides a theoretical basis for analysis of ecosystem responses (Webster et al. 1975, Waide and Swank 1976) and may provide a useful tool for assessing effects on health and sustainability. *Resistance* is defined as the magnitude of a response parameter from initial conditions, and *resilience* is the duration of response. One of the key parameters of ecosystem response is biogeochemical cycling. We propose that the magnitude (e.g., resistance) and duration (e.g., resilience) of NO_3 response in stream water may be a useful metric for assessing ecosystem response to burning in the southern Appalachians. In this study, our objectives were to summarize and compare stream NO_3–N responses from four southern Appalachian watersheds receiving different burn prescriptions, and to identify factors that contribute to varying responses.

STUDY SITES

All four burned areas were on the Nantahala National Forest in western North Carolina. Annual rainfall in the region ranges from 1,800 to 2,300 mm, and annual temperature averages approximately 14 °C and ranges from an average of 7 °C during the dormant season to 19 °C during the growing season. Three of the four sites were characterized as the xeric oak–pine forest type, in a generally degraded condition due to the combined effects of land-management practices (e.g., high-grade logging), fire exclusion, and drought. Stands typically consisted of mixtures of pitch pine (*Pinus rigida*), Virginia pine (*P. virginiana*), shortleaf pine (*P. elliottii*), scarlet oak (*Quercus coccinea*), chestnut oak (*Q. prinus*), and red maple (*Acer rubrum*), and have dense understories of the ericaceous shrub mountain laurel (*Kalmia latifolia*). Much of the yellow pine (*Pinus* spp.) overstory on these sites was dead because of recent drought-related southern pine beetle (*Dendroctonus frontalis*) infestations (Smith 1991). In addition, many of the oak species (*Quercus* spp.), especially members of the red oak group, were either dead or in a serious state of decline (Starkey et al. 1989, Clinton et al. 1993*a*). Within the burned areas (Table 1), riparian vegetation makes up a small fraction of the total area.

The fourth site was within the Joyce Kilmer-Slickrock Wilderness Area and Memorial Forest, located approximately 60 km west of the other three sites. The area has an old-growth designation and is one of the few remaining large uncut forested tracts in the southern Appalachians. This high-elevation site contains large areas of both mesic and xeric forest types. Woody species composition in the mesic coves is typical of the southern Appalachians; however, with more large downed and standing dead wood, larger standing live trees, and a higher canopy height, the stand is substantially different from the other forest systems examined here.

METHODS

Due to the degraded condition of xeric oak–pine stands in the southern Appalachians, the fell-and-burn site preparation prescription (Abercrombie and Sims 1986) is recommended to restore their commercial viability and enhance other attributes of ecosystem health (Vose et al. 1999). In 1990 a 5.25-ha watershed, designated Jacobs Branch (JB), was selected to examine effects of the fell-and-burn treatment from an ecosystem perspective. Initial and long-term results have been published in a suite of papers (see Clinton et al. 1993*b*, 1996; Elliott and Vose 1993, 1995; Knoepp and Swank 1993, 1995; Swift et al. 1993; Vose and Swank 1993; Clinton and Vose 2000), and a complete burning characterization has been described by Swift et al. (1993). Jacobs Branch is approximately 5 km north of Franklin, North Carolina (35°N, 83°W), has a southwesterly aspect, and is approximately 765 m in elevation with slopes ranging from 35% to 50%. In brief, all woody vegetation on JB was felled during summer 1990. The downed material was allowed to cure for approximately 10 weeks before a headfire was set at the base of the slope. The entire slope burned in <30 minutes. The fire was characterized as a high-intensity, low-severity fire. Stream samples were collected weekly from a small stream at the base of the burned watershed beginning 6 months prior to burning and continued for more than 12 months after burning. Weekly samples were composited to obtain a monthly mean.

Winespring Creek (WSC) is approximately 10 km west of Franklin, North Carolina (35°N, 83°W), has a southerly aspect, and ranges in elevation from 1,500 m to 1,700 m with slopes ranging from 35% to 60%. The burn was implemented in April 1995 to simulate a stand-replacement wildfire covering approximately 82 ha. The fire prescription was designed to examine the effects of wildfire on responses of vegetation, soil processes, and stream chemistry and turbidity (Major 1996; Vose et al. 1997, 1999; Elliott et al. 1999). The site was ignited by a helicopter and helitorch using strip headfires along the contour beginning at the lower- and mid-slope positions. Crown fires were frequent at mid- and upper-slope positions due to the combination of heavy fuels, steep slopes, thick mountain laurel understories, and firing techniques. Streams and roads provided natural fire-breaks, and a backing fire was set along the top of the ridge. Automated time-increment proportional stream samplers (American Sigma, Loveland, CO) were installed in 1993 at the base of the burned slope and upstream of the burned area, as well as in several streams in other unburned areas to be used as references to characterize dissolved inorganic chemistry. In addition, grab samples (e.g., 250-ml collections at designated locations) were collected weekly at each stream sampler location.

The Joyce Kilmer-Slick Rock Wilderness Area (JK) is located in Graham County in western North Carolina and Monroe County in eastern Tennessee (35°N, 84°W). It covers 5,040 ha, has an easterly aspect, and ranges in elevation from 1,200 m to 1,600 m. An arson wildfire in November 1999 burned approximately 970 ha, or about two-thirds of the Little Santeetlah Creek Watershed within the JK site. In essence, the fire was an understory burn that traveled well into riparian zones of many small streams draining the watershed. During the time of the burn, stream samples were being collected for an unrelated study of stream-water chemistry. On the JK site, weekly grab samples were taken beginning in August 1999 and continued for 6 months after the burn.

Hickory Branch (HB) is a 486-ha, south-facing watershed and ranges in elevation from 1,100 m to 1,280 m. In March 1999, a simulated wildfire was applied to the HB site. The site was strip-burned with a helitorch along the contour beginning at the ridge and continuing to the base of the watershed. Crown fires frequently occurred on steep, south-facing slopes containing standing dead yellow pine snags and thick mountain laurel understories. Approximately 75% of the watershed burned. Stream-water grab samples were taken weekly beginning approximately 12 months before the burn at the watershed outlet on Pine Branch (hereafter referred to as Lower Pine Branch) and at two locations upstream immediately above the confluence of Pine Branch (Upper Pine Branch) and Matheson Branch. Approximately 2 weeks before the burn, an automated flow-increment proportional sampler (American Sigma, Loveland, CO) was installed at the watershed outlet (Lower Pine Branch), which collected samples for 2 months after the burn. Grab samples continued to be collected at all three collection sites. No fire characterization or pre-burn estimates of woody and fine fuels were conducted on this watershed.

All stream-water samples were analyzed at the Coweeta Hydrologic Lab using established protocols (Deal et al. 1996) for determination of nitrate–nitrogen (NO_3–N) concentrations using a Dionex ion chromatograph (Dionex, Sunnyvale, CA). To account for seasonal differences and provide long-term baseline values (28+ yr), monthly mean stream NO_3 concentration for a south-facing mixed-hardwood control watershed at Coweeta (Watershed 2) was used as an undisturbed reference for stream NO_3 concentration.

Since the data used in this paper were derived from unreplicated (and retrospective) watershed scale studies, we have limited our analyses to descriptive statistics and qualitative comparisons of temporal variation in stream [NO_3] relative to baseline (or control) conditions. While this approach limits the ability to make inferences about responses in other watersheds and burning treatments, the long-term and integrative nature of watershed-scale studies has long been recognized as a powerful approach for understanding ecosystem responses to disturbance (e.g., Swank and Vose 1997).

RESULTS

Stream responses to burning varied among the four burned areas in NO_3 concentration and timing. Following the JB burn, NO_3–N in stream water increased from <0.01 mg N L^{-1} to 0.055 mg N L^{-1} after 3 months and up to a maximum of 0.075 mg L^{-1} after 7 months, and remained elevated until June of the fol-

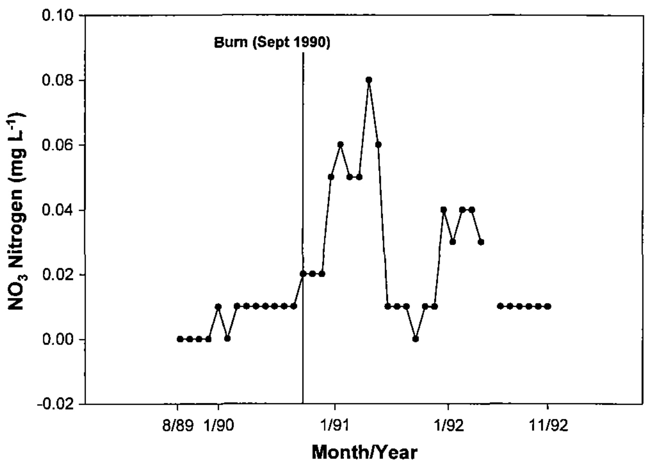

Fig. 1. Pre- and post-burn stream NO_3–N responses at the Jacobs Branch fell-and-burn site on the Nantahala National Forest, North Carolina.

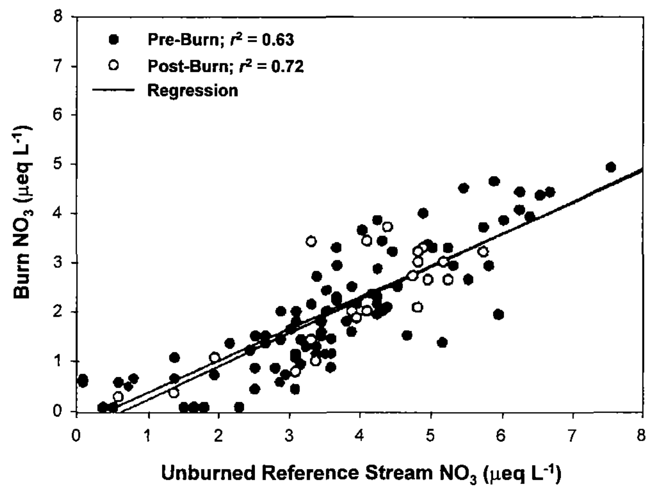

Fig. 2. Stream NO_3–N response to stand-replacement burning on the Winespring Creek site on the Nantahala National Forest, North Carolina. Regressions represent a least squares fit to pre- and post-burn plots of NO_3 concentrations in a stream draining an unburned reference watershed against the burned watershed. Significant differences in the slopes of the regressions were evaluated at the $P < 0.10$ level.

lowing year (Figure 1). Nitrate then returned to pretreatment levels. Early stream NO_3–N increases in September prior to burning (Figure 1) may be attributed to the release of NO_3–N due to the cutting treatment.

On the WSC watershed, stream-water chemistry, which was measured for 29 months after burning, showed no measurable fire effect on stream NO_3–N levels. For example, using pre- and post-burn regressions of stream NO_3, Vose et al. (1999) detected no significant differences ($P < 0.10$) in NO_3 concentrations between the stream directly below the burned area and an unburned reference stream (Figure 2). Furthermore, values for NO_3 concentration for post-burn storms on the burned watershed stream were well within the range of values observed for the same post-burn storms on the reference stand (Vose et al. 1999).

Stream-water NO_3 concentration following the JK wildfire showed a marked increase over pre-burn values. Compared to the values for the previous 2 months, NO_3 rose from a low of 0.02 mg N L^{-1} to 0.12 mg N L^{-1} within 6 weeks of the burn but quickly returned to near pre-burn values (Figure 3).

In contrast, the HB burn showed little or no response to the fire. There were strong similarities in monthly mean stream-water NO_3 concentrations between the HB burn site and an undisturbed reference watershed at the Coweeta Hydrologic Laboratory both in terms of the magnitude and the seasonality before and after the burn (Figure 3). Nitrate concentrations during the growing season were slightly higher than on the reference watershed, but dormant-season values were similar. There were some marginal differences among the three sample locations within the HB watershed in response to burning. A small increase in NO_3 concentrations 2 weeks following burning in Upper Pine and Matheson Branch was observed (Figure 4), but the response was not detectible at the watershed outlet in Lower Pine Branch.

DISCUSSION

Site differences, species composition, riparian zone condition, and type and season of burning influenced observed differences in the amount and duration of stream-water NO_3 responses (Table 2). Large differences were observed between fall burns (September and November) and spring burns (March and April). The two sites that burned in the fall (JB and JK) show large increases in NO_3 concentration compared to the spring burns (WSC and HB). For example, the two sites that showed a NO_3 response were burned in early and late fall when vegetation uptake and microbial im-

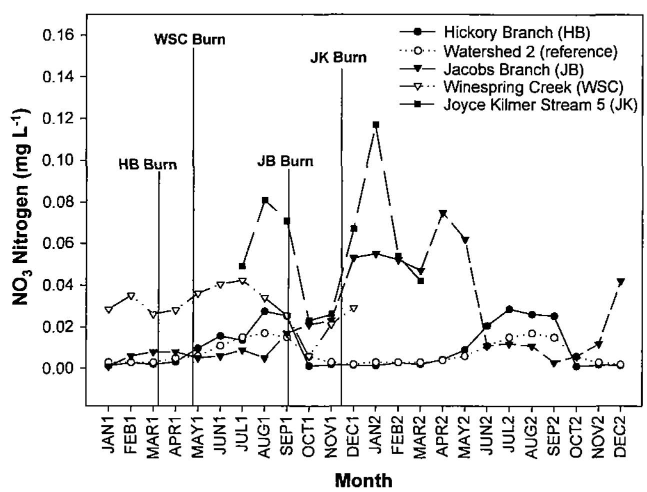

Fig. 3. Pre- and post-burn stream NO_3–N responses for Jacobs Branch, Winespring Creek, Joyce-Kilmer Wilderness, and Hickory Branch watersheds on the Nantahala National Forest, North Carolina, in relation to an undisturbed reference watershed (Watershed 2) at the Coweeta Hydrologic Laboratory. Watershed 2 represents long-term baseline stream nitrogen dynamics.

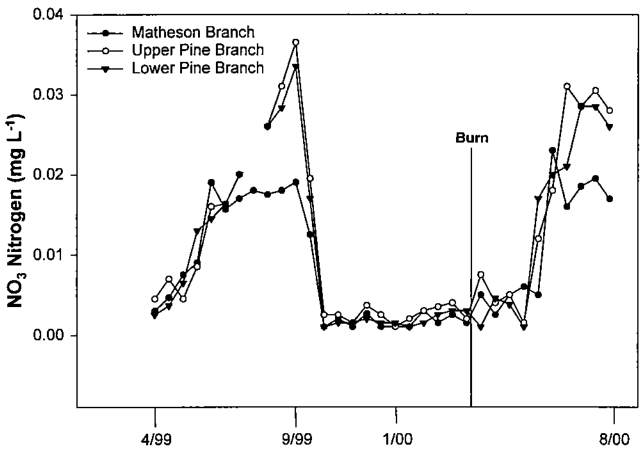

Fig. 4. Bi-weekly mean pre- and post-burn stream NO_3 concentrations for the Hickory Branch site on the Nantahala National Forest, North Carolina.

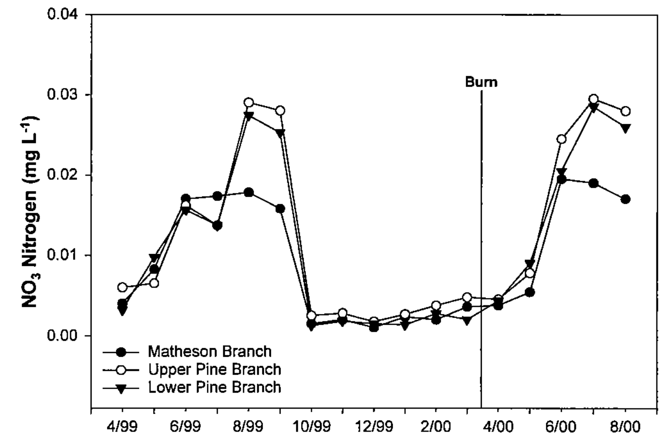

Fig. 5. Monthly mean pre- and post-burn stream NO_3 concentrations for the Hickory Branch site on the Nantahala National Forest, North Carolina.

mobilization were low. On the JB site, Knoepp and Swank (1993) observed significant increases in soil water NO_3 concentration at 30- and 60-cm depths soon after the burn in September and a sharp increase again in June the next year. The initial post-burn increase was likely due to leaching of excess NO_3 resulting from reduced uptake and increased mineralization (Knoepp and Swank 1993), and the later increase was probably related to increased decomposition of exposed surface organic layers and other fine organic material and delayed increases in rates of nitrification often observed following fire (Knoepp and Swank 1993, White 1996). Because virtually no uptake of soil nutrients was taking place during the dormant season, and because of vegetation removal to within a few meters of the stream, available NO_3–N was leached to the stream. To some extent, the same explanation can be used for observed increases in stream NO_3 concentration following the JK burn. In late fall, no vegetation uptake was occurring to immobilize excess NO_3. Additionally, some of the riparian areas were burned, therefore providing a potential direct input of NO_3 to the stream.

The streams that showed no measurable response (HB and WSC) drained watersheds that burned in early spring at the onset of leaf growth and nutrient uptake. Hence, vegetation that was not killed by the fire may have immobilized NO_3 via uptake. In addition, riparian vegetation, particularly evergreen shrubs, may play an important role in mitigating disturbance in early spring before leaf expansion of deciduous species. For example, evergreen shrubs (particularly *Rhododendron maximum,* but *Kalmia latifolia* to a lesser extent), which are typical of riparian vegetation in the southern Appalachians, begin photosynthesis at air temperatures near 10 °C and nutrient sequestration when soil temperatures are near 5 °C (E.T. Nilsen, Virginia Polytechnic and State University, personal communication). In addition, J.M. Vose (unpublished data) demonstrated the effectiveness of riparian zones in reducing NO_3 delivery to streams through microbial uptake. On the WSC site, the riparian zone served to buffer fire effects because it did not burn (Vose et al. 1999). Similarly, the riparian zone on the HB site, although burned in mid-March, may have immobilized most of the NO_3 mobilized during the burn, since only a weak stream-water NO_3 response in the upper reaches of the watershed was on the HB site 2 weeks after burning.

There were some unexplained within-watershed differences in NO_3 response among the three sampling sites unrelated to the burn (Figure 5). For example, Matheson Branch had consistently lower NO_3 values during the growing season than Upper and Lower Pine Branch locations. Concentrations of NO_3 in Lower Pine Branch were intermediate compared to Matheson and Upper Pine Branch, probably as a result of dilution (higher flow volumes) and possibly in-stream uptake (Webster et al. 1991).

Table 2. Comparison of burn type, season of burn, and NO_3 response amount and duration among four watersheds on the Nantahala National Forest, North Carolina. The magnitude of response represents resistance to disturbance and duration of response represents resilience.

Site	Fire type	Time of burn	NO_3 response (mg N L^{-1})	Magnitude (%)[a]	NO_3 response duration
Jacobs Branch	Fell and burn	September 1990	0.065	+750	30 weeks
Winespring Creek	Stand replacement	April 1995	0	0	None
Hickory Branch	Stand replacement	March 2000	0.0045	+250	2 weeks
Joyce Kilmer	Old-growth wildfire	November 1999	0.10	+600	6 weeks

[a] Percent increase above pre-burn NO_3 concentrations.

Table 3. Pre-burn woody fuel loadings, forest floor mass, and nitrogen pools for the fell-and-burned site (Jacobs Branch), a stand-replacement burned site (Winespring Creek), and the old-growth wildfire (Joyce Kilmer) on the Nantahala National Forest, North Carolina. Values represent watershed means.

Site	Burning treatment	Fuel category[a]	Mass (kg ha^{-1})	Nitrogen (kg ha^{-1})
Jacobs Branch (JB)	Fell and burn	Woody fuels	183,717	429
		Forest floor	24,000	217
Winespring Creek (WSC)	Stand replacement	Woody fuels	15,773	43
		Forest floor	23,240	314
Joyce Kilmer (JK)	Old-growth wildfire	Woody fuels	39,233	N/A
		Forest floor	26,670	365

[a] Woody fuels represents dead material and includes all woody material >7.5-cm diameter that was felled prior to burning on the JB site; on the WSC and JK sites, woody fuels refers to downed woody material >7.5-cm diameter.

Influence of Fuels

Increased consumption of forest-floor fuels during burning often results in accelerated NO_3 losses from the site (Covington and Sackett 1992, Vose and Swank 1993) due to a combination of volatilization, increased mobilization, and reduced uptake. Some of the variation in stream NO_3 losses among burns may be related to differences in the amount and quality of forest floor fuels. For example, the fell-and-burn site (JB) had extremely high woody fuel loadings because all standing vegetation was felled prior to burning (Table 3). Higher-severity fires resulting from the heavy fuel loads have the potential to reduce the vigor of re-growing vegetation and reduce nutrient uptake (Elliott et al. 2002). For example, stream NO_3 response on the JB site suggested low resistance (+750%) and resilience (30-week duration). This is likely due to high-intensity and high-severity fires, which reduce the ability of vegetation regrowth to mediate the effects of burning. In contrast, the stand-replacement burns showed high resistance and resilience to disturbance due in part to lower fuels (hence, lower-intensity and lower-severity fires), an intact riparian buffer, and season of the burn. The JK wildfire was intermediate in resilience but less resistant to disturbance, possibly due to the typical, old-growth forest-floor characteristics (e.g., large accumulations of recalcitrant nitrogen). Another possible explanation for the pulse of NO_3 following the JK wildfire is low resistance to disturbance in old-growth forest ecosystems. There is some evidence to suggest that old-growth forests are less capable of sequestering nutrients mobilized by disturbance than actively growing, aggrading forest ecosystems. In addition, stand age, in the absence of fire, determines the accumulation of recalcitrant forms of N that are released during burning and become subject to volatilization and leaching from the system.

CONCLUSIONS

The qualitative analyses of retrospective studies presented here suggests that stream [NO_3] response to prescribed burning is a function of the interactions among site variables, burn type, and burn timing. Timing is important because of the link between phenology, vegetation growth, and nutrient cycling processes. Riparian vegetation may also play an important role in mitigating effects of fire on stream-water chemistry, probably by sequestering mobilized nutrients. The two sites that burned in the fall showed increased stream-water NO_3, probably because nutrient uptake rates are low during that time of the year. In the case of the fell-and-burn treatment, all major nutrient pools (e.g., wood, foliage, forest floor layers) were partially consumed, and considering the timing of this burn (fall), the likelihood of a stream chemistry response was highest among all the sites. Even under these conditions, stream NO_3 concentration responses were low, and where increases in stream-water NO_3 occurred, concentrations were below levels of concern for either water quality or site productivity (Knoepp and Swank 1993). These results suggest that the implementation of Best Management Practices were effective in minimizing stream NO_3.

Resistance and resilience concepts present a potential approach for assessing ecosystem responses to prescribed fire. Watersheds responding with the greatest magnitude and duration (i.e., JB and JK) in stream NO_3 had attributes that were consistent with responses predicted by resistance and resilience theory. For example, high fire severity coupled with a fall burn at JB limited the ability of the ecosystem to sequester excess NO_3 for a longer time period than the other burns (i.e., less resistance and resilience). Similarly, we surmise that slow growth rates and a fall burn were the primary factors resulting in similar patterns at JK.

Our results here suggest that slight modifications in the timing of burning and maintenance of intact riparian zones will ensure that effects on stream NO_3 concentration are minimal and of short duration. Since these conclusions are based principally on unreplicated watershed-scale experiments, further studies will be required to increase our ability to infer responses in other watersheds and burning regimes.

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